IMPLEMENTATION OF DEFLECTION BOWL MEASUREMENTS FOR STRUCTURAL EVALUATIONS AT NETWORK LEVEL OF AIRPORT PAVEMENT MANAGEMENT SYSTEM

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ABSTRACT

The APMS is a useful tool for operators and managers, providing a systematic and objective method for pavement condition evaluation, maintenance planning decisions and budget allocation. The pavement evaluation process also includes the evaluation of structural capacity and, more specifically, the use of deflectometer testing device has become a basic part of the structural evaluation, allowing non-destructive and rapid to execute surveys. The measured deflection bowl is used for the back-analysis process in order to evaluate the modulus of each layer. This application can be less cost effective, requiring experienced analyst and often providing more detail than necessary, especially for implementation at network-level of Airport PMS. These aspects are amplified for seasonal and regional airports, faced with low budget availability and looking for easy and rapid techniques. The investigation reported in this paper focused on developing a direct method for the assessment of the overall conditions as well as single layer strength, based on deflections measured by performing HWD tests. The data collected by deflectometer campaign performed on the runway has been analyzed, focusing the attention on the factors that can affect the measurements.

The survey was performed on five alignments, according to the international regulations, in different seasons and with different loads, then the relative influence was examined, conducting a correlation aimed on comparing deflections. With comparable data, the immediately visual rating of deflection values has been conducted, adopting the relative benchmarking methodology. The implementation at network level of Airport PMS allows the rapid overview of structural conditions, identifying areas that need further detailed investigations.

INTRODUCTION

The development of new, rapid and easy tools for the assessment of structural conditions of paved areas as runways, taxiways and aprons, is a key objective for regional and seasonal airports, usually faced with low budget availability for pavement evaluation. As air transportation demand increase and average aircraft size too, greater attention must be focused on pavement performance analysis and model prediction, especially for implementation on Airport Pavement Management System (APMS), including structural evaluations as well as visual distress, roughness and texture properties. Deflection testing method is currently widely used for rapid and non-destructive evaluation of the structural capacity. The deflectometric device applies a stationary dynamic load to measure the induced deflection basin in the tested pavement then back-calculation analysis could be used normally assuming multi-layered elastic theory [1]. The back-calculation process can have some inaccuracies due to assumptions and modelling approaches then running into various problems of credibility due to the uncertainties regarding material characterization, uniqueness of measuring equipment, personal interpretations, confusion of dynamic and static response and basic material variability [2]. Also, generally provides more details than necessary for decision trees, making it less attractive and less cost effective for network-level applications of APMS. The key is to improve each technique in such a way that a simple parameter (or set of parameters) can be computed to describe the overall structural capacity of a uniform pavement section [3]. In the last years, attention has been focused on deflection bowl investigation in order to obtain pavement evaluation without back-calculation analysis process and estimating relative damage [4]. Pavement deflection measurements are important inputs to many pavement condition assessment tools, including structural capacity indicator tools and tools to calculate the remaining service life of pavements [5].

An overall rating of pavement load carrying capacity can be directly obtained by analyzing deflection measured, helping operators to best evaluate the appropriate decisions on pavement maintenance without the need of back-analysis process [6]. At the network level the maximum surface deflection under the load, obtained from structural capacity testing is probably all that is required to assess the structural capacity of a pavement [7] [8]. Anyway, maximum deflection describes how the overall pavement system behaves under a load, but not necessarily, how the individual layers are going to resist fatigue or permanent deformation [9]. Correlations between a number of deflection bowl parameters and mechanistically determined structural evaluations of a number of pavement types offer the possibility to use these parameters in a semi-ME fashion to analyze pavements. The parameters can also be used in a complementary fashion with visual surveys and other assessment methodologies to describe pavement structural layers as sound, warning or severe in respect of their structural capacities and behavior states [10]. The deflection bowl parameters can be used in a benchmarking procedure to help identify weaker areas in pavements over length and width as well as in-depth of the pavement structure (identify structurally weak layers) to help optimize further detailed investigations [1]. This benchmarking methodology with the associated condition ratings helps to accurately identify uniform sections and pinpoint the cause of structural distress, often seen only as various forms of surface distress, and helps to explain the mechanism of deterioration [11].

This study focused the attention on structural conditions evaluation by investigating and comparing the data collected from two deflectometric campaigns conducted at the Olbia airport with the Heavy Falling Weight Deflectometer (HWD).

RESEARCH OBJECTIVE

In order to develop and validate the use of a set of parameters for the assessment of structural conditions directly using deflection values, the data provided by the airport management company collected from two deflectometric campaigns has been analyzed. The analysis aimed on knowing the overall structural capacity as well single layer conditions, investigating the maximum deflection values and three parameters related to HMA, subbase and subgrade layers respectively. The surveys have been conducted in two different seasons and with different loads then data has been normalized to a reference load allowing the comparison and the implementation at network level of APMS. The selection of the benchmarking values for pavement condition rating as acceptable, warning and severe, has been conducted by comparing the E-moduli values obtained from back-calculation. With the use of contour plots can be easily appreciated the variations over length and width helping to rapidly identify areas that need further detailed investigations.

THE OLBIA “COSTA SMERALDA” AIRPORT

The surveys were conducted at the Olbia “Costa Smeralda” Airport. It is a single runway regional airport, located in the northeastern coast in the island of Sardinia (Italy), with approximately 29,000 annual aircrafts movements. It is a mild climate region all year round, without experiencing freeze thaw seasons. The peculiarity of this airport consists in the high seasonality of movements, with a peak of more than 7,000 movements on summer, when hot and dry conditions occurs, as noticeable in Figure 1.

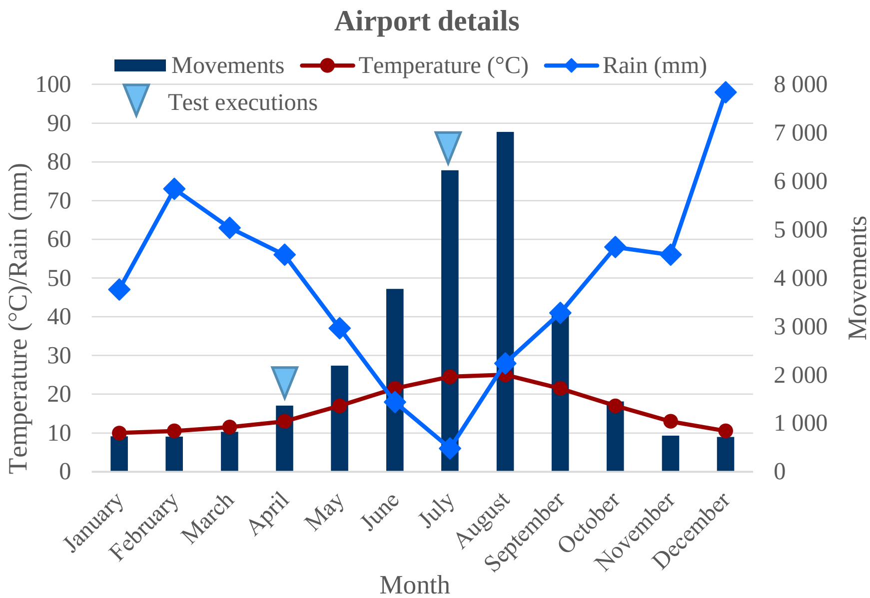

Figure 1. Airport details (5 year trend)

More specifically, the 70% of movements are distributed between June and September, while the remaining 30% is distributed throughout the rest of the year. This is also a rather peculiar case in Italy because the airport management company is held by a commercial airline and here are located the operational headquarters of an aircraft's maintenance company. The surveys were conducted along the runway (Figure 2), having a total length of 2,445 meters (TORA), of which 2,150 meters are in standard flexible pavement with bituminous stabilized base, while the remaining part, located on each threshold, is semi-rigid paved.

Figure 2. Olbia "Costa Smeralda" Airport layout

According to the Ground Penetrating Radar (GPR) survey inspections the main AC layer thickness is 290 mm, with peaks of 330 mm, and the main thickness of the granular subbase is 400 mm. Thickness variations are related to maintenance works executed only on fixed sections. A standard runway section is represented on Figure 3.

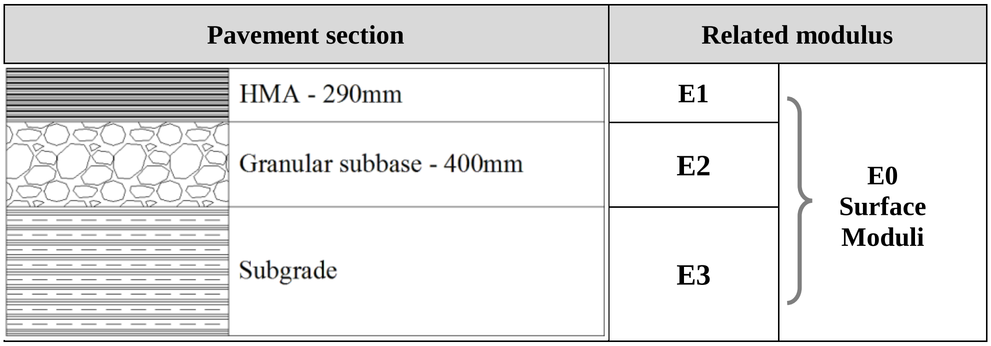

Figure 3. Typical inspected runway section.

TESTS CONDUCTED

The tests were conducted with a Dynatest HWD 8082 trailer (Figure 4), in two different sessions, along five alignments: at centerline and with a lateral offset of 3.00 m and 5.20 m (left and right) from centerline, according to the recommendations provided by ICAO [12] and FAA [13] [14], spacing 100 m. The deflections were measured at the center load (D1) and with a distance of 200 mm (D2), 300 mm (D3), 450 mm (D4), 600 mm (D5), 900 mm (D6), 1200 mm (D7), 1500 mm (D8) and 1800 mm (D9).

Figure 4. The Dynatest HWD device

The first survey was carried out in April 2013, at the end of the rainy season and with a pavement's temperature of 15°C. A total of 105 points were investigated covering the whole flexible runway. The second survey was carried out in July 2013, during the hot and dry period, with an average temperature of the pavement of 35 °C. Two test sections, TS1 and TS2, respectively 500 and 900 meters long, as shown on Figure 5, were investigated applying different loads. A total of 80 points were analyzed.

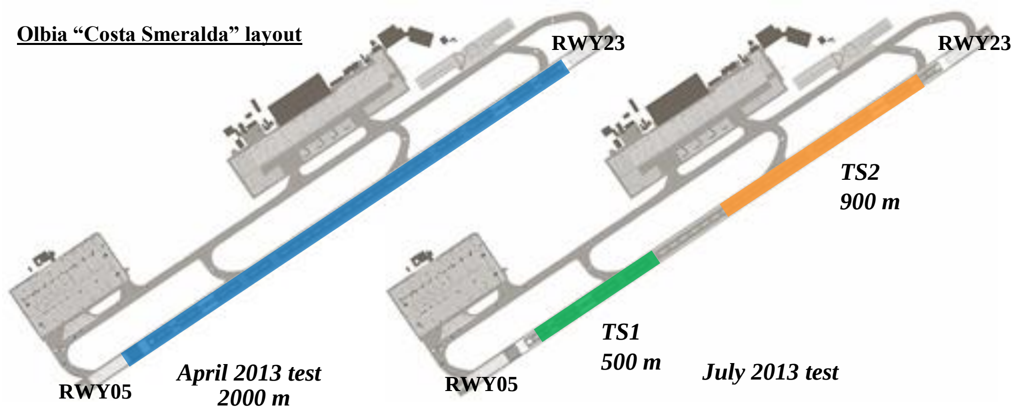

Figure 5. April and July tests localization

DATA ANALYS

The collected raw data has been investigated in order to assess the structural condition of the HMA, granular subbase and subgrade layers, analyzing the maximum deflection and the basin shape. Studies conducted throughout years demonstrated the relationship of basin shape with pavement's layer (see Figure 6).

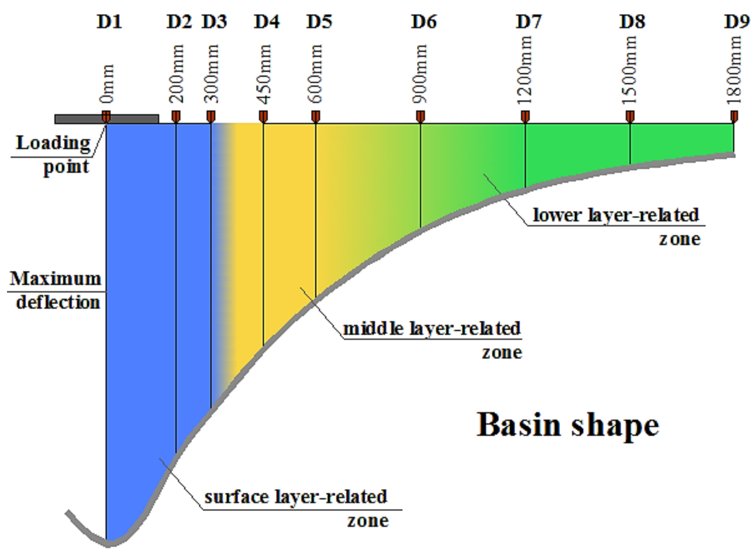

Figure 6. Standard basin shape measured

The structural capacity of the upper layer is related to the basin shape closest to the loading point, where a positive curvature can be noticed, usually ranging between geophones D1 (0 mm) and D3 (300 mm). The unbound granular subbase behavior is related to the middle area of basin shape, usually referring from D3 up to D5 (900 mm), while the farthest deflections, from D5 to D9 (1800 mm) are related to the subgrade characteristics. The data analysis process focused on knowing the relationship between selected deflection parameters and the moduli obtained with the back-calculation process, then using them to set benchmarking values. The back-calculation has been conducted with the commercial software ELMOD, provided by Dynatest. The type of materials used both for subbase and subgrade layers has been defined by coring inspections carried out on the inspected field.

April tests

The first session of tests has been characterized by almost the same load impulse of 145 kN, applying a pressure equal to 2052 kPa. Pavement response has shown the worst performance between the alignments +5,20m and 3,00m, where the greater values of the maximum deflection, over 1800 μm, were measured, while best conditions were noticed at the centerline. Also the highest standard deviation σ values were noticed along the alignments +5,20m and 3,00m. The effect of greater deflections and highest standard deviation is probably related to the ducts serving centerline lighting system crossing the runway each 60 m. Low maintenance activity allows water's infiltration causing cracking and, therefore, the reduction of stiffness and service life of the involved layers.

To investigate the structural capacity of upper bounded layers the attention has been focused on the surface curvature index (SCI) defined as:

$$SCI = D1 - D3 \qquad (1)$$

The correlation between these parameters and the modulus of AC layer, E1, obtained by back-calculation process was investigated, founding a good correlation with the SCI.

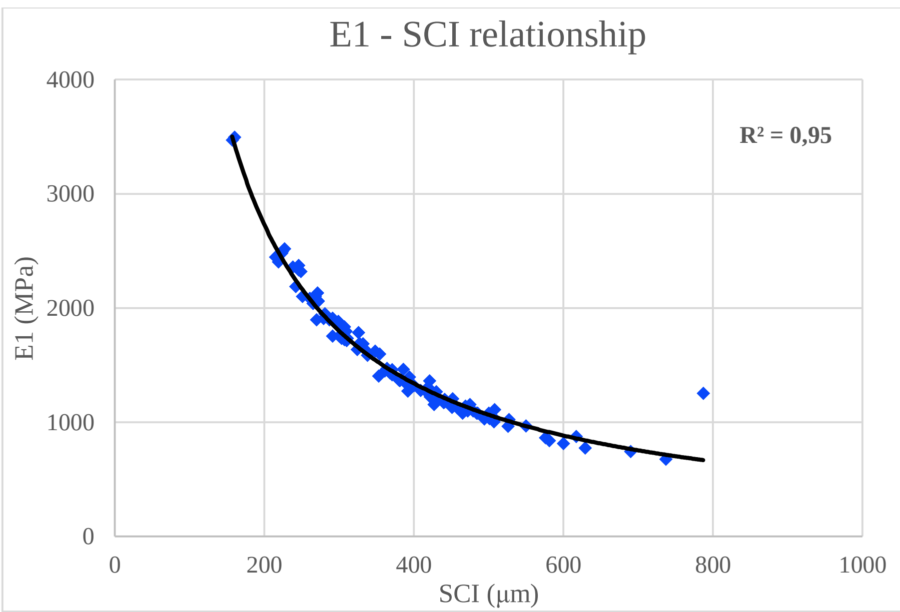

Figure 7. Surface modulus – SCI relationship

The correlation is expressed by using the formula:

$$E1 = 629629\ (SCI)^{-1,03} \qquad (2)$$

The middle layer investigated is a granular subbase and for the purpose of this work has been adopted the modified base damage index, proposed by Donovan and Tutumluer [4]:

$$Modified\ BDI = D3 - D5 \qquad (3)$$

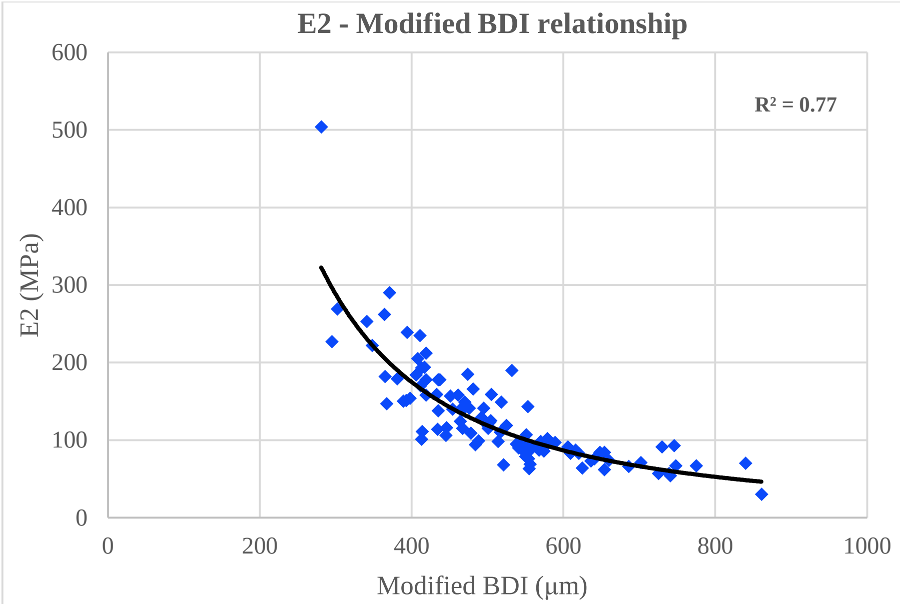

Figure 8. Unbound granular subbase – BDI mod relationship

The correlation is expressed by using the formula:

$$E2 = 5663607\ (\text{Modified BDI})^{-1{,}73} \qquad (4)$$

The evaluation of the subgrade layer properties were conducted by using a Subgrade index (R^2=0.62, Figure 9) instead of the Modified BCI (D6 – D8) proposed by Donovan and Tutumluer [4] (R^2=0.41), defined by the ratio of Modified BCI and the D5 (600 mm) deflection. The relationship appear to be more clear for values of SI greater than 0.37 of SI, becoming less reliable whit lower values.

$$SI = (D6 - D8) / D5 \qquad (5)$$

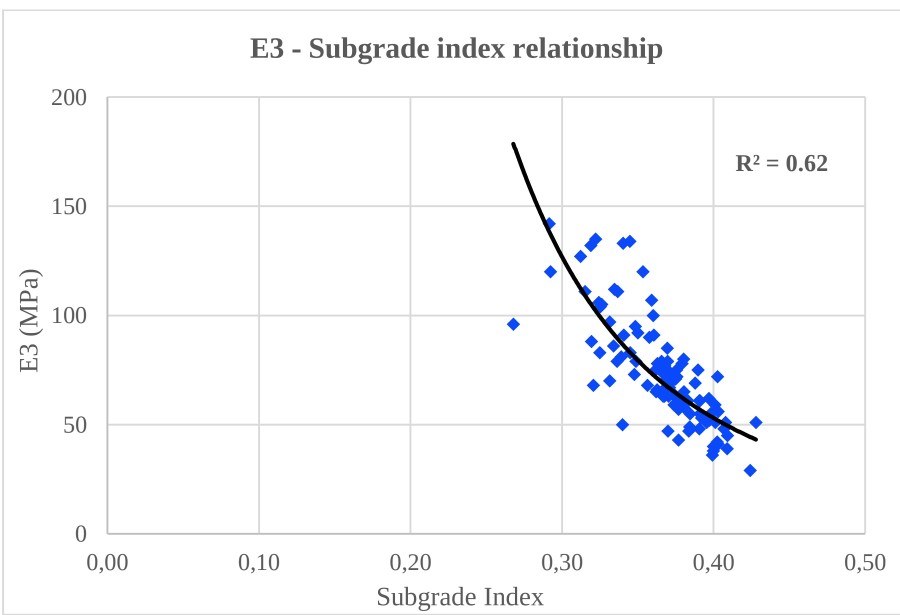

Figure 9. E3 - Subgrade index relationship

The correlation is expressed by using the formula:

$$E3 = 3{,}30(SI)^{-3.03} \quad (6)$$

July tests

The second deflection survey was executed applying different loads corresponding to 70 kN, 92 kN, 106 kN and 113 kN. Unfortunately, the applied loads were completely different from the first survey, thus in order to avoid misleading conclusions collected data were normalized.

DATA COMPARISON

To make comparable the results obtained from the two test campaigns, two indices were introduced, looking for an easy relationship by applying the linear interpolation method. The first index proposed is the load ratio *Lr*, defined as the ratio between the load impulse of July tests and the load impulse of April tests. The second index is the deflection ratio *Dr*, defined as the ratio between the deflection of the *i* geophone obtained in July and the deflection of the *i* geophone obtained in April, as reported by following equations:

$$Lr = (Load_{july})/(Load_{april}) \quad (7)$$

$$Dr = (Deflection\ i\text{-}geophone_{july})/(Deflection\ i\text{-}geophone_{april}) \quad (8)$$

Or, in general terms:

$$Lr = (Load_{execution})/(Load_{reference}) \quad (9)$$

$$Dr = (Deflection\ i\text{-}geophone_{execution})/(Deflection\ i\text{-}geophone_{reference}) \quad (10)$$

Table 1. Load ratio vs Deflection ratio results

Dr index	D1	0.58	0.60	0.76	0.84	0.81	0.82	0.85	0.82	Softening by high temperatures
	D2	0.55	0.57	0.73	0.79	0.77	0.79	0.82	0.82	
	D3	0.53	0.55	0.70	0.76	0.76	0.78	0.80	0.80	
	D4	0.52	0.52	0.69	0.72	0.74	0.76	0.79	0.79	
	D5	0.50	0.49	0.67	0.69	0.73	0.75	0.78	0.76	---------------
	D6	0.45	0.45	0.67	0.65	0.72	0.75	0.74	0.71	Hardening by moisture reduction
	D7	0.43	0.45	0.68	0.64	0.72	0.77	0.74	0.72	
	D8	0.40	0.41	0.65	0.66	0.69	0.72	0.70	0.74	
	D9	0.39	0.41	0.64	0.68	0.67	0.69	0.70	0.66	
Lr index		**0.48**	**0.49**	**0.64**	**0.72**	**0.73**	**0.74**	**0.77**	**0.78**	

The analysis of the indexes highlighted the relationship of layers with specific deflection bowl areas. A linear interpolation was established using *Dr* values, with R^2 ranging from a minimum of = 0.90 (D7) up to 1.00 (D3), as shown on Figure 10. Also Garg and Marsey [15] investigated on the relationship load-deflection experiencing a fairly linear relationship for D1 (0 mm) and D6 (1500 mm) deflection values with different load impulses ranging between 55 and 160kN.

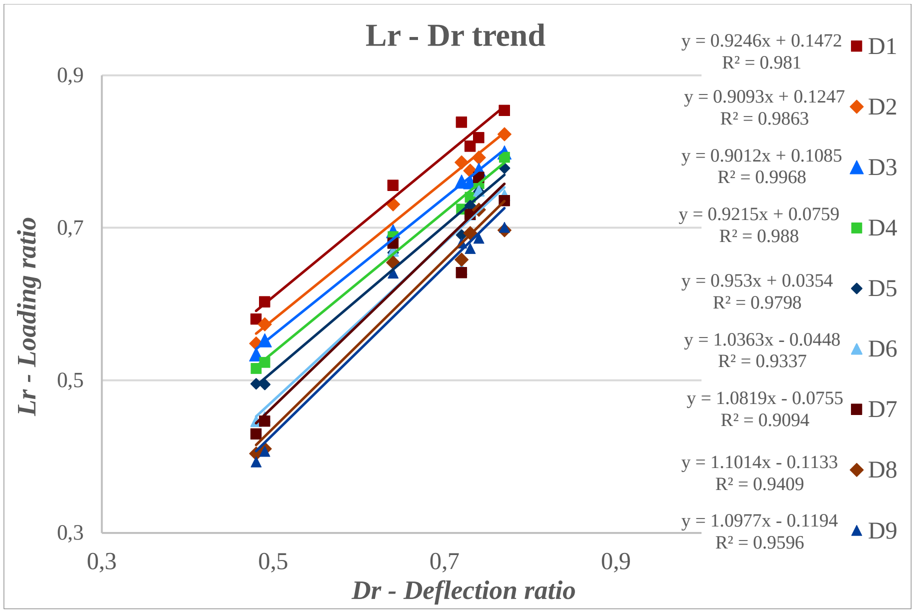

Figure 10. Geophones interpolation Dr – Lr

These correlations have been used to normalize deflections obtained on summer tests to conduct a comparison with previous data gathered. Analyzing the results obtained applying the load correction on July 2013 tests, greater deflections of the upper layers then the values measured on April 2013 tests were determined (*Dr/Lr >1*). This effect is due to the lower stiffness of asphalt concrete layers which, of course, decreases with high summer temperatures. On the other hand, the stiffness of the lower unbounded layers was greater on test conducted in July 2013, as expected, since the moisture content was lower than the spring values (*Dr/Lr <1*). On Figure 11 a representation of measured and theoretical basin shapes for two different loads were reported. The measured deflection field for a load of 70 kN has a different trend from to the expected basin shape, drawn applying just the loading ratio percentage.

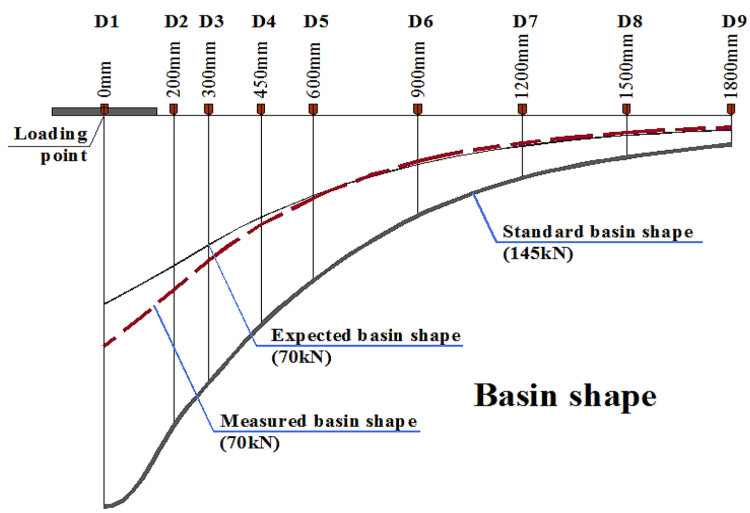

Figure 11. Basin shape comparison

Figure 12 shows as the increase of the load magnitude affects the deflection parameters while the E modulus of each layer continues to be the same, as expected.

Figure 12. Effect of load magnitude on layer's moduli.

BENCHMARKING APPLICATION

In order to define a relative structural benchmarking application for deflection evaluation at network-level, the different tiered condition-rating description proposed by Horak [1] [10], known as RAG system (Red-Amber-Green), has been adopted. Three levels of structural conditions were related to the colors selected, corresponding to weak, poor and acceptable pavement response. Donovan and Tutumluer [4] investigated on the use of a relative damage of layers by comparing deflections measured from traffic and non-traffic lanes and Eijbersen and Zweiten [16] too investigated on referencing deflections of wheel path lane with non-wheel path lane deflections. In this case, the application of the proposed method cannot be conducted due to uncertainties related to the assumption of reference values and amount of traffic and load distribution during service life. The selection of the benchmarking values involved the results of the back-calculation process, even though there are some limitations on assumptions that operators cannot overlook.

The first step of the benchmarking procedure involved the maximum deflection D1. Best conditions can be noticed on center line, most probably related to the lower stress applied by the nose gear load. A set of benchmarking values had been proposed (Table 2), allowing also corrections to improve sensitivity of evaluation or enhancements suggested by future investigations. The first normalization application has been applied to the maximum deflection (see Figure 13). As discussed, the manipulation of center load deflections allows overall assessment about pavement conditions.

Table 2. Benchmark values proposed – D1

Pavement	Structural condition rating	D1 (*drop weight 145kN*)
HMA with *Bituminous Base*	Acceptable (Green)	< 1200 (μm)
	Warning (Amber)	1200 - 1600 (μm)
	Severe (Red)	> 1600 (μm)

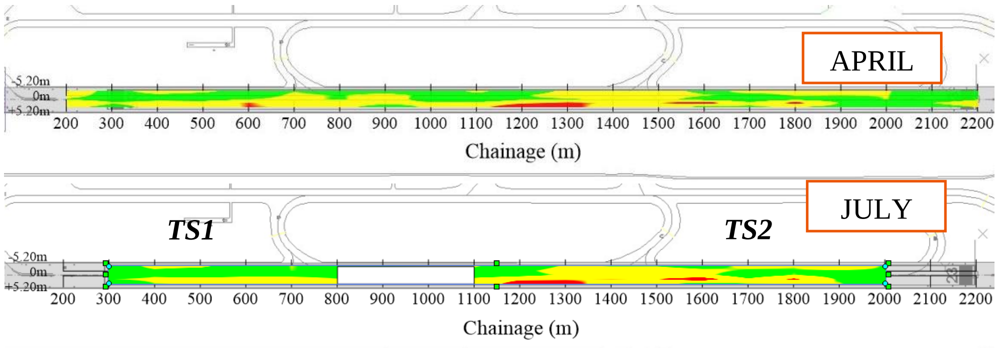

Figure 13. Contour plot comparison of D1 (April) and D1 (July) normalized

The Figure 13 shows how the maximum deflection value changes over the inspected field, highlighting higher values corresponding from progressive 1200 m to 1300 m. By the analysis of deflection values and the aquifer monitoring program conducted with 11 piezometer distributed on the inspected area, higher deflections appear to be related to the effect of water table variations, as outlined on Figure 14.

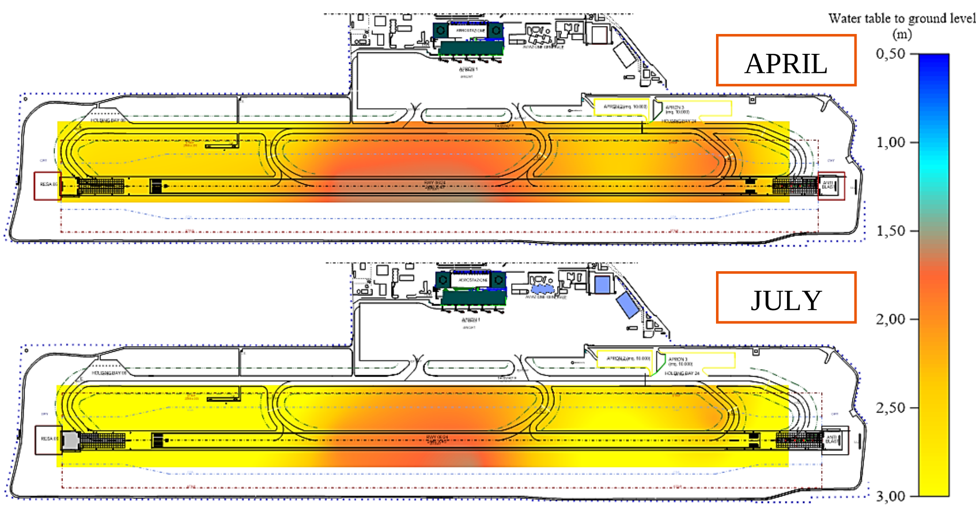

Figure 14. Aquifer variation (April – July)

Then the attention focused on the single layer capacity. By managing equations 2, 4 and 6, referring to literature review for the selection of E benchmarking values, it has been possible to fix the three performance-related levels. The use of contour plot technique using Table 3 and Table 4 values helps to compare data providing information about the surface conditions. Figure 15 and Figure 16 show the reliability of structural rating by using the SCI index both for April and July 2013 tests.

Table 3. Benchmark values selected for E1

Layer	Structural condition rating	E1 (MPa)
HMA with *Bituminous Base*	Acceptable (Green)	> 2250 (MPa)
	Warning (Amber)	2250 - 1250 (MPa)
	Severe (Red)	< 1250 (MPa)

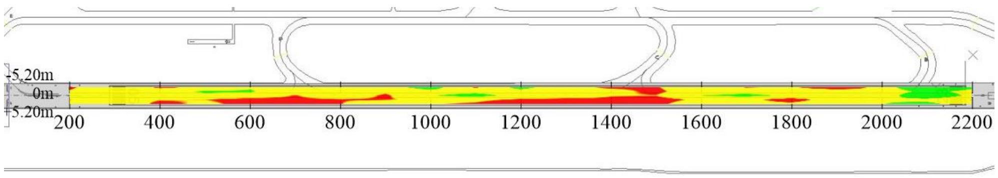

Figure 15. Contour plot of benchmarking application of E1

Table 4. Benchmark values proposed – SCI

Layer	Structural condition rating	SCI (*drop weight 145kN*)
HMA with *Bituminous Base*	Acceptable (Green)	< 245(μm)
	Warning (Amber)	245 - 425 (μm)
	Severe (Red)	> 425 (μm)

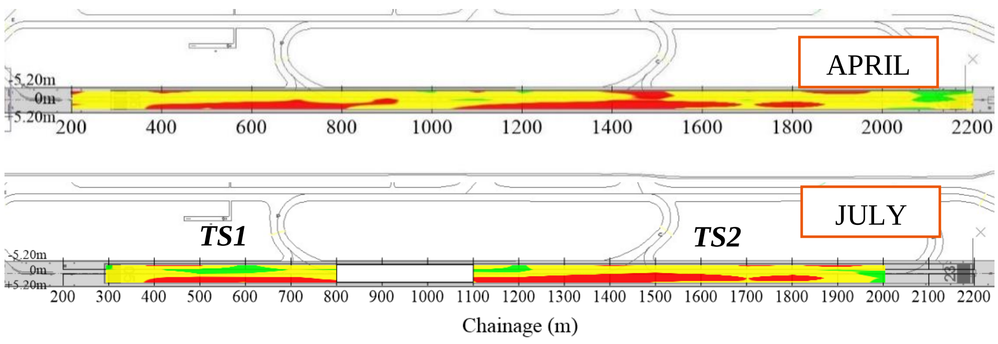

Figure 16. Contour plot comparison of SCI (April) and SCI (July) normalized

Also for the subbase rating condition has been applied the comparison between deflection values and the E2 modulus in order to set the relative benchmarking values (Table 5), then using Equation 4 it has been possible to set the *Modified BDI* values (Table 6). In this case, as noticeable by comparing contour plots of Figure 17 and Figure 18, the evaluation of subbase layer allows reliable overall assessments. Few differences can be noticed on isolated points.

Table 5. Benchmark values selected for E2

Layer	Structural condition rating	E2 (MPa)
Subbase	Acceptable (Green)	> 200 (MPa)
	Warning (Amber)	200 - 100 (MPa)
	Severe (Red)	< 100 (MPa)

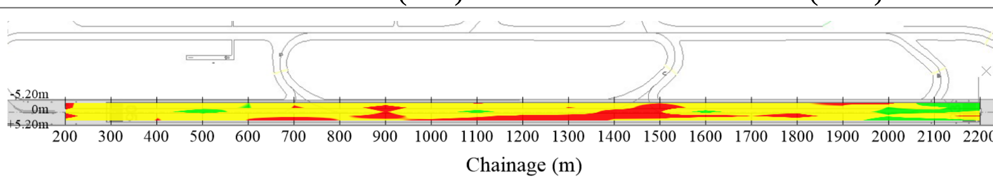

Figure 17. Contour plot of benchmarking application for E2

Table 6. Benchmark values proposed – BDI mod

Layer	Structural condition rating	Modified BDI (*drop weight 145kN*)
Subbase	Acceptable (Green)	< 375 (μm)
	Warning (Amber)	375 - 565 (μm)
	Severe (Red)	> 565 (μm)

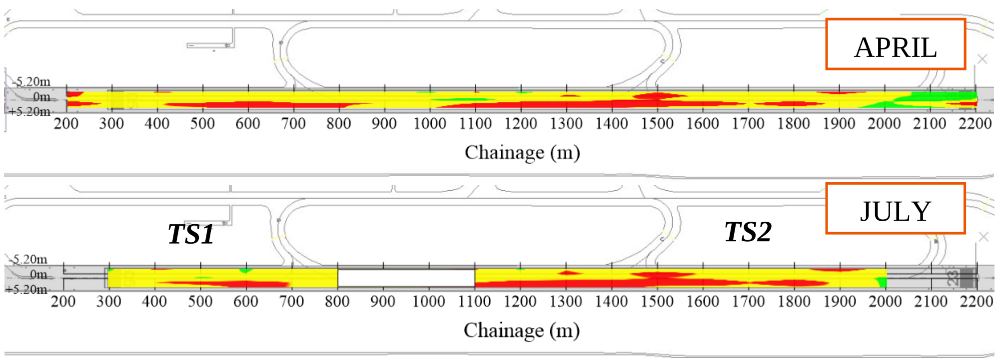

Figure 18. Contour plot comparison of BDI mod (April) and BDI mod (July) normalized

The application of the technique has been applied also for the investigation of subgrade. As upper layers, the benchmarking values of E3 (Table 7) have been used for the condition rating procedure. Figure 19 shows the results over length and width of the back-calculation.

Table 7. Benchmark values selected for E3

Layer	Structural condition rating	E3 (MPa)
Subgrade	Acceptable (Green)	> 100 (MPa)
	Warning (Amber)	100- 50 (MPa)
	Severe (Red)	< 50 (MPa)

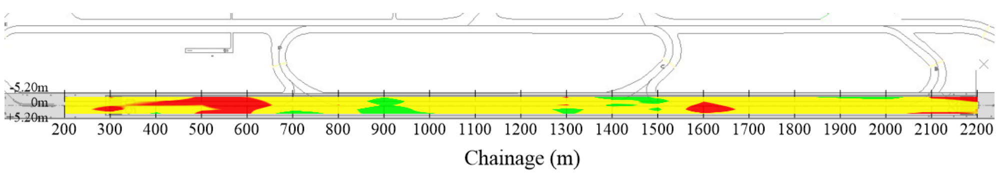

Figure 19. Contour plot of benchmarking application for E3

Table 8. Benchmark values proposed – Subgrade Index

Layer	Structural condition rating	Subgrade Index (*drop weight 145kN*)
Subgrade	Acceptable (Green)	< 0.325
	Warning (Amber)	0.325 – 0.340(μm)
	Severe (Red)	> 0.340 (μm)

Even though the correlation decreases, the technique allows the visual identification of sections with different behavior. In this case, the normalization of data shows an overall increase of the inspected field. This aspect could be related to the lower moisture and the lower load applied.

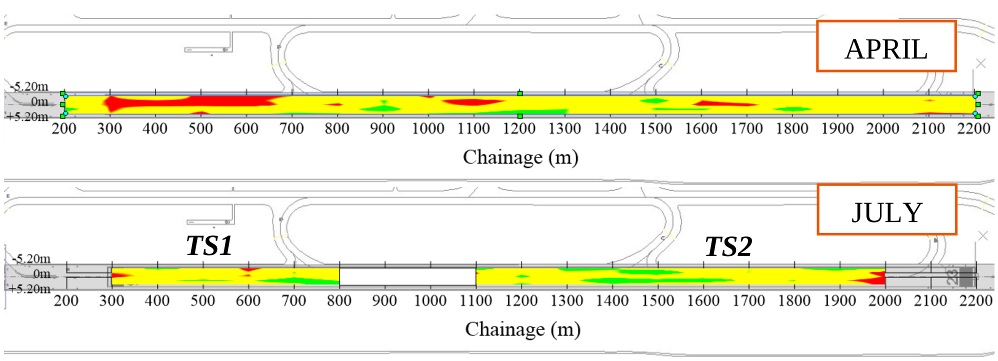

Figure 20. Contour plot comparison of SI (April) and SI (July) normalized

CONCLUSIONS

The goal of this investigation is to set a rapid-to-execute and standardized framework for the analysis and comparison of deflection values gathered on different tests. The use of deflection values has been investigated for implementation at network-level of APMS, aiming on evaluating both overall and single layer structural capacity without recurring to the back-analysis process in future. In this paper the deflection values obtained from two different campaign, conducted with the non-destructive HWD testing device, were discussed. Two test sections of the runway of Olbia "Costa Smeralda" airport, respectively length 500 m and 900 m, were investigated in different climatic conditions and with different load impulses.

Due to the differences of loads applied between April 2013 and July 2013 test sessions, the comparison was conducted introducing two indexes, the load ratio *Lr* and the deflection ratio *Dr*. Since layers properties are related to the deflections measured , this application highlighted the different response of geophones regarding the position from center load. The deflections from D1 to D3 are related to the surface layer characteristics, showing higher deflections than expected due to the increased pavement's temperature of summer tests. The deflections from D7 to D9 are related to the subgrade layer, showing lower deflections than expected due to the decrease of moisture.

Having different pavement's responses in regard to loads applied and geophones considered, then to the layer inspected, the normalization of values has been conducted assuming the different relationship established for the selected geophone. The normalization of data has been successfully applied to the maximum deflection values (*D1*), and to the parameters Surface curvature index (*SCI*), Modified Base damage index (*BDI mod*) and to Subgrade Index (*SI*), allowing the comparison of data even though obtained in different conditions. This application could be used for future evaluations of layers inspected.

Then the benchmarking application has been applied using the three-tiered condition rating approach, allowing the immediately visual assessment of structural capacity and identifying areas that need further detailed investigations. To validate findings, the ongoing research should focus on validating benchmark values proposed and focusing the attention on the seasonal effect.

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